JOURNAL OF AGRICULTURAL RESEARCH
DEPARTMENT OF AGRICULTURE

VOL. VII WASHINGTON, D. C., DECEMBER 4, 1916 NO. 10

NITRIFICATION IN SEMIARID SOILS—I.[1]

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HISTORICAL INTRODUCTION

The distribution and amounts of nitrogen in the humus of the arid and semiarid soils of America and the activities of the microorganisms contained therein have been discussed at length by a number of writers. It has been especially emphasized that, as a rule, the humus and nitrogen are distributed more uniformly to a greater depth in the subsoil of the arid than of the humid regions. The soils are commonly very deep and are not sharply separated from the subsoils, but the actual percentage of nitrogen in the surface soil is frequently low and usually decreases in passing downward into the subsoil. The soils and subsoils in many parts of California, for example, contain less than 0.05 per cent of nitrogen and in many localities even less than 0.03 per cent.

Hilgard (10),[3] Loughridge (26), Lipman (16), and others have directed attention to the great depth of root penetration in the semiarid region, and Loughridge has suggested that the apparent deficiency of nitrogen in the surface soils may be compensated for by the distribution of nitrogen in the deep subsoils. He finds, for example, that the total nitrogen in the zone occupied by plant roots commonly compares favorably with that in humid regions. But, as is well known, the application of nitrogenous fertilizers commonly results in marked stimulation to crops, and in many localities successful crop production depends upon the use of nitrogenous fertilizers. As much as 1,000 to 1,500 pounds of dried blood per acre has been applied annually to some of the Citrus groves of southern California, and in some cases as much as 2,000 pounds per acre has been applied. Corresponding amounts of other nitrogenous materials have been used.

[1] Paper 35, Citrus Experiment Station, College of Agriculture, University of California, Riverside, Cal.
[2] The writer acknowledges the valuable analytical assistance of Mr. A. B. Cummins.
[3] Reference is made by number to "Literature cited," p. 436-437.

In the course of investigations on the origin of the so-called "niter spots" in Colorado, Sackett (28) concluded that nitrification is unusually active in Colorado soils and more so than in soils from certain other Western States. Stewart, Greaves, and coworkers (31, 32, 33, 34) in Utah concluded, on the other hand, that the excessive accumulation of nitrates in the surface soils of certain localities is to be accounted for mainly by the capillary rise of nitrates from deeper strata rather than from unusual nitrifying activity in the soils at the present time.

Lipman (16), by the use of the modified Remy solution method, found that ammonification and nitrification are most active in the first foot of California soils, but in some cases these processes were also found to take place quite actively in the subsoils down to a depth of 8 to 10 feet. He concluded that the deep penetration of the roots of cultivated plants may be accounted for in part by the active formation of available nitrogen in the deep substrata. McBeth and Smith (27) also found from experiments with the use of actual soil as the culture medium that dried blood and ammonium sulphate undergo active nitrification in the first foot of certain Utah soils, but the activity was found to decrease markedly in the successive sections below the first foot until at a depth of 4 or more feet it almost ceased. In their experiments about 90 per cent of the total nitrate produced in the 5-foot sections studied was formed in the first foot, from which it would seem that nitrification is not particularly active in the substrata below the first foot.

Greaves (8) found that, as a rule, cultivation brings about an increase in the numbers of organisms and in the rates of nitrification and nitrogen fixation in certain soils of Utah; he has also studied the effects of different arsenic compounds on the biological activities in soils (7, 9). Lipman and Burgess (17, 18, 19, 22, 23) have devoted considerable study to the effects of alkali salts and small amounts of copper, zinc, iron, and lead compounds on ammonification and nitrification in California soils.

Recently Lipman and Burgess (24) published experiments on the rates of nitrification of different fertilizers in 29 different soils from California. Briefly, it was found that, on the whole, ammonium sulphate was most actively and quite vigorously nitrified in most of the soils studied. The rates at which the different organic substances underwent nitrification varied widely. In certain soils low in organic matter little or no nitrate was formed from dried blood or high-grade tankage, while at the same time cottonseed meal, bone meal, garbage tankage, and other low-nitrogen-containing materials were quite vigorously nitrified. They concluded as follows:

> In all soils of our interior arid valleys which are not very close to stream channels or those which for other reasons are markedly deficient in organic matter, the proper bacteriological and perhaps other conditions do not obtain to render into nitrates most economically and quickly the nitrogen of high-grade organic nitrogenous fertilizers. On the other hand, conditions in those same soils are much more favorable for the nitrification of nitrogen of the low grade nitrogenous fertilizers. Similar con-

ditions prevail in the humus-poor soils of our coast valleys and of other valleys in the state, in which either the soils have always been deficient in organic matter or have become depleted in that respect through excessive oxidation under favorable climatic conditions assisted by constant summer cultivation.

In connection with the above and other investigations, Lipman has found that ammonification is active in California soils generally and that in some cases greater amounts of ammonia than nitrate occur in soil samples freshly drawn from the field. This condition was especially noted in soils on which the plant diseases known as dieback and mottle-leaf of *Citrus* spp. occur. In these soils Lipman (20, 21) found nitrification to be inactive. He suggested a causal relationship between the active ammonification and inactive nitrification on the one hand and the abnormal plant growth on the other, the latter being attributed to enforced ammonia absorption occasioned by the inability of the soil to transform ammonium nitrogen into nitrates.

As contrasted with the above hypothesis, Kellerman and Wright (11) have pointed out that the physiological disease known as mottle-leaf of Citrus trees may be caused by excessive accumulations of nitrates in the soil; but the source of the nitrate, whether being actively formed at the present time or otherwise, is not clear from their publication.

Beckwith, Vass, and Robinson (3) have studied the effects of lime on the ammonification of dried blood and peptone, and the nitrification of dried blood and ammonium sulphate in six soils from Oregon. In every case they found that active ammonification took place, but in two of the soils less nitrate was found after four weeks' incubation where either dried blood or ammonium sulphate had been added than in the portions to which no nitrogenous material was added. In one case the further addition of lime failed to induce the nitrification of these materials. An increase in the nitrate content in the check portions was found in every case, indicating the presence of the nitrifying organisms in the soil.

From the foregoing partial review of the literature on this subject it is apparent that radical differences of opinion are held with reference both to the formation and the movement of nitrates in the soils of the semiarid region.

In view of the economic importance of nitrogen and the scientific interest attached to nitrification, the writer has for some time been engaged in a series of studies on this subject at the University of California Citrus Experiment Station, at Riverside, Cal. At this place a fertilizer experiment with Citrus trees has been maintained during the past nine years. The plots of this experiment and other semiarid soils near by have been used in these investigations and have made it possible to compare the data obtained in the laboratory studies with the effects produced in the field.

The relative rates of nitrification in the field and laboratory, the effects of soil treatments including different fertilizers, manure, and cover

crops, the effects of alkali salts, the relative nitrifiability of different fertilizing substances, seasonable variation in nitrification, the movement of nitrates, and other phases of this question are being studied. The results obtained in the early stages of this work strongly emphasized the need for further study of the methods to be used.

In the previous studies on nitrification in semiarid soil the Remy-solution method, with certain modifications, has been used to a limited extent; but usually the direct-soil method has been used, in which actual soil is employed as the culture medium.[1] Different investigators, however, have modified the details to suit their own ideas. These modifications have to do mainly with variations in temperature, moisture content, and periods of incubation on the one hand, and differences in the ratio of soil to nitrogenous materials on the other. Regarding the latter it is noteworthy that the percentage of nitrogenous, organic material employed has been varied from about 0.7 to 2 per cent. In the case of ammonium sulphate the variations have ranged from 0.1 to 1 per cent.

Likewise, widely variant percentages of actual nitrogen from different sources have been added by one and the same investigator. For example, Lipman and Burgess (24) employed equal weights (1 per cent) of calcium cyanamid, dried blood, bone meal, high-grade tankage, cottonseed meal, manure, etc.; but since the nitrogen content of these materials ranged from 2.46 per cent to 16.55 per cent, the actual quantities of nitrogen added must have varied accordingly. Ammonium sulphate was added at the rate of 0.2 per cent. On the basis of the data thus obtained, deductions were made concerning the relative nitrifiability of these materials. Likewise, McBeth and Smith (27) added dried blood and ammonium sulphate at the rates of 1 and 0.08 per cent, respectively; and while the absolute amounts of nitrate formed from the latter were considerably larger than from the former, no particular notice was given to it, an average of the results from the two forms being recorded in many cases.

Before presenting the full data bearing upon the specific subjects named above, the present paper will be devoted to a discussion of the methods commonly employed in laboratory studies on nitrification with special reference to the concentration of nitrogenous materials and period of incubation used. In most cases the phenol-disulphonic-acid method was used for the determination of nitrate. At frequent intervals throughout this investigation the aluminum reduction method as outlined by Burgess (5) was also used for the purpose of checking the results obtained by the colorimetric method. The results by the two methods were found to agree closely in all cases, except where high concentrations of nitroge-

[1] It is not deemed necessary to discuss in detail the advantages and disadvantages of these two methods. The reader is referred to a paper by Löhnis and Green (25) in which a critical review of the subject is given. Some of the points emphasized below were also strongly emphasized by them two years previously.

nous materials or other abnormal conditions were employed. In such cases the results by the reduction method were frequently much higher than by the colorimetric method. Further reference will be made to this point later. It is recognized that the colorimetric method is not accurate where high concentrations of nitrate occur, but the results are believed to be sufficiently accurate for the purposes of this paper.

EXPERIMENTAL WORK

The soil used was for the most part drawn from the fertilizer plots[1] referred to above. This soil has been derived from the disintegration of monzonite and is a light, sandy loam, very low in organic matter and nitrogen. It is underlain with a deep subsoil similar in nature to the surface soil. A composite sample composed of about 20 borings was obtained from each plot sampled and also from the virgin soil[2] near by. The samples were taken to a depth of 6 inches with a King soil tube and were then immediately brought to the laboratory and spread out on clean paper to dry. After becoming air-dry and being thoroughly mixed, duplicate portions of 150 gm. were mixed in tumblers with 1.5 gm. of dried blood, and the moisture content made up to 15 per cent with distilled water, after which the samples were incubated at 25° to 28° C.

In order to ascertain the formation of ammonia, 50-gm. portions were withdrawn at the end of 7 and 28 days, and the ammonia determined by distilling with an excess of magnesium oxid, and at the end of 28 days the nitric nitrogen was determined. The average of closely agreeing duplicates is recorded in Table I.

TABLE I.—*Ammonification and nitrification of 1 per cent dried blood (in parts per million)*

Soil.	Ammonia nitrogen.		Nitric nitrogen.	
	After 7 days.	After 28 days.	Original soil.	Gain in 28 days.
Virgin	584	385	1.2	5.5
Control plot	503	400	2.1	2.5
Manured plot	497	287	8.4	241.6

The foregoing data show that active ammonification took place in the soil from each plot studied and that a relatively high concentration of ammonia still occurred at the end of 28 days. The lesser amount of ammonia found in each case at the end of 28 days was probably due in part to the loss of ammonia by volatilization. Strong odors of ammonia were detected, especially in the tumblers containing the virgin soil and

[1] It is not deemed necessary at this point to discuss in detail the different treatments that have been applied in the field experiments. A more complete discussion will be presented in a subsequent paper.

[2] The term "virgin soil" as used in this paper signifies uncultivated soil still bearing native vegetation.

that from the control plot. It is not deemed necessary to dwell further on the ammonification of organic materials in these soils. Suffice it to say that the ammonia has been determined in a large number of instances throughout this work and without exception ammonification has been found to be active in every soil studied. The above data on ammonification are submitted merely to show that nitrification was not limited by inactive ammonification and not as a special contribution to the study of ammonification.

Considering the amounts of nitric nitrogen found, it will be noted that little or no nitrification took place except in the soil previously treated with manure. In this case quite active nitrification took place. It is of special interest that only the most enfeebled nitrification of dried blood took place in the virgin soil; and although slightly more nitrate was formed in the virgin soil than in the check plot, the difference is too small to be noteworthy.

Two of the plots (C and S) in the field experiments from which the above samples were drawn have been annually fertilized with dried blood for the past nine years (1907–1915). During the past two years (1914–15) the application has been made at the rate of 1,080 pounds per acre. Notable stimulation in the growth and yield of fruit has been produced. One of these plots (C) lies adjacent to the check plot used in the foregoing experiments. Soil samples drawn at frequent intervals during the past two years from this and other plots fertilized with dried blood have consistently shown a well-defined increase in nitric nitrogen over that in the unfertilized plots. Furthermore, considerable increases in the nitrate content have been found following each application of dried blood. It would seem, therefore, that dried blood undergoes active nitrification in the field where no other form of organic matter has been applied, notwithstanding the fact that the above data indicate that both the virgin soil and control plot are unable to nitrify dried blood.

Two questions presented themselves: First, why does dried blood undergo active nitrification in the field but not in the laboratory? Second, why is it that dried blood undergoes active nitrification in the soil from the manured plot but apparently not in the control plot? Considerations arising out of these questions have led to an extended study of the factors affecting nitrification in the field and laboratory.

NITRIFICATION AS AFFECTED BY VARYING CONCENTRATIONS OF MATERIALS

As stated above, 1,080 pounds of dried blood per acre have been applied annually for the past two years (1914–15) to plots C and S. Until the present year (1916) only one-third of this quantity was applied at one time, the remaining two-thirds being applied at intervals of about two months each. But assuming that the entire amount becomes thoroughly mixed with the soil to a depth of 6 inches and estimating that the

soil weighs 2,000,000 pounds per acre of 6 inches, the average concentration of dried blood that obtains in the field would be 0.054 per cent. On the other hand, a concentration of 1 per cent was employed in the preceding laboratory experiments, which is 18.5 times that which obtains in the field.

It was at once suggested that an excessive concentration had been used in the laboratory. Accordingly a preliminary set of experiments was made, in which widely different concentrations of dried blood were added. The result was that the soil from the plots which had previously failed to nitrify a 1 per cent concentration of dried blood was found to support active nitrification of this material when added in low concentrations.

An extended study has been made on the rates of nitrification of different nitrogenous materials when used in varying concentrations. Fresh samples were drawn from the same plots as in the preceding series. The nitrogeneous materials used were dried blood, bone meal, and ammonium sulphate, representing a high-grade and a low-grade organic form and an inorganic compound, respectively. The dried blood (13.20 per cent of nitrogen) was added in quantities ranging from 1 to 0.0625 per cent. The bone meal (4.25 per cent of nitrogen) was varied from 4 to 0.25 per cent. Ammonium sulphate (21 per cent of nitrogen) was varied from 0.6 to 0.0375 per cent. The experiments were made in duplicate. Control portions of each soil without the addition of nitrogenous material were also incubated. The incubation period was four weeks. The results are given in Table II.

TABLE II.—*Nitrification as affected by different concentrations of nitrogenous materials*

Materials added.	Nitrogen added per 100 gm. of soil.	Virgin soil.		Control plot.		Manured plot.	
		Nitric nitrogen found.	Percentage nitrified.	Nitric nitrogen found.	Percentage nitrified.	Nitric nitrogen found.	Percentage nitrified.
	Mgm.	*P. p. m.*		*P. p. m.*		*P. p. m.*	
None	0	34.0	.....	19.6	.....	38.7	.....
Dried blood:							
1.0 per cent	132.0	22.0	0	3.8	0	316.0	21.0
0.5 per cent	66.0	42.0	1.2	21.0	0.2	248.0	31.7
0.25 per cent	33.0	57.5	7.1	120.0	30.4	140.0	30.7
0.125 per cent	16.5	111.0	46.6	99.0	48.1	96.0	34.8
0.0625 per cent	8.25	73.0	47.3	75.0	67.1	82.0	52.5
Bone meal:							
4.0 per cent	170.0	24.5	0	18.9	0	188.0	8.8
2.0 per cent	85.0	51.5	2.1	27.5	0.9	240.0	23.7
1.0 per cent	42.5	109.0	17.7	96.0	17.9	220.0	42.7
0.5 per cent	21.25	99.5	30.9	104.0	39.7	150.0	52.4
0.25 per cent	10.62	80.0	43.3	69.0	46.5	91.0	49.3
Ammonium sulphate:							
0.6 per cent	126.0	15.4	0	31.0	0.9	94.0	4.4
0.3 per cent	63.0	53.0	3.0	63.0	6.9	176.0	21.8
0.15 per cent	31.5	65.0	9.8	82.0	19.8	158.0	37.9
0.075 per cent	15.7	78.0	28.0	88.0	43.6	148.0	69.6
0.0375 per cent	7.85	69.0	44.6	74.0	69.3	112.0	93.4
Original soil	.....	1.8	.....	4.5	.....	13.6	.....

As shown above, 1 per cent of dried blood failed to be nitrified in the virgin soil and that from the control plot, but underwent active nitrification in the previously manured soil as in the preceding series. The larger quantities of bone meal and ammonium sulphate also failed to be nitrified, but the lower concentrations of each of these substances underwent active nitrification in every case. Dried blood in a concentration of 0.625 per cent, which corresponds closely with that used in the field, underwent active nitrification in all cases. The percentages of nitrification, calculated after subtracting the amounts of nitric nitrogen found in the control portions, show that when corresponding amounts of actual nitrogen from the different sources are compared the rates of nitrification of dried blood, bone meal, and ammonium sulphate were quite similar in all cases with the single exception of ammonium sulphate in the manured soil. In this case ammonium sulphate was oxidized the most completely of any of the materials studied.[1]

Soils from other localities have also been studied. Two samples were obtained from the lemon groves of a ranch in Ventura County. One of these (A) is a light sandy soil; the other (B), a heavy adobe soil high in organic matter. A sample was taken from a young lemon grove on another ranch in Ventura County and is a heavy clay soil, containing considerable organic matter. Another sample of a light sandy character was taken from an orange grove opposite the Lark Ellen station near Covina. A sandy loam containing considerable gravel and organic matter was obtained from a 24-year-old orange grove in the La Verne section in southern California.

Studies were made in duplicate with the use of the same materials as in the preceding series. Since a 2 per cent concentration of dried blood (8, 13, 18) has been previously used to some extent in studies on nitrification, this proportion was added in certain cases. The concentrations of bone meal were varied from 4 to 0.5 per cent, and of ammonium sulphate, from 0.3 to 0.075 per cent. The results are given in Table III.

TABLE III.—*Nitrification in soils from different localities*

Materials added.	Nitrogen added per 100 gm. of soil.	Sespe soil (A).		Sespe soil (B).		Limoneira soil.		Lark Ellen soil.		La Verne soil.	
		Nitric nitrogen found.	Percentage nitrified.	Nitric nitrogen found.	Percentage nitrified.	Nitric nitrogen found.	Percentage nitrified.	Nitric nitrogen found.	Percentage nitrified.	Nitric nitrogen found.	Percentage nitrified.
	Mgm.	*P.p.m.*		*P.p.m.*		*P.p.m.*		*P.p.m.*		*P.p.m.*	
None	0	61.0	.....	38.5	.....	49.0	.....	86.0	.....	34.0	.....
Dried blood:											
2.0 per cent	264.0	.....	.....	.....	.....	6.5	0	24.5	0	.....	.....
1.0 per cent	132.0	736.0	51.1	360.0	24.3	468.0	31.7	107.0	1.6	442.5	30.9
0.125 per cent	16.5	170.0	66.1	129.0	54.9	163.0	69.1	191.0	63.6	144.0	66.6
Bone meal:											
4.0 per cent	170.0	220.0	9.4	224.0	10.9	332.0	16.6	76.0	0	.....	.....
1.0 per cent	42.5	.....	.....	.....	.....	196.0	34.6	222.0	32.0	.....	.....
0.5 per cent	21.25	186.0	58.8	136.0	45.9	152.0	48.5	168.0	38.6	140.0	49.8
Ammonium sulphate:											
0.3 per cent	63.0	228.0	26.5	111.5	11.6	128.0	12.5	162.0	12.1	.....	.....
0.75 per cent	15.75	206.0	92.1	106.0	42.9	148.0	62.9	172.0	54.6	124.0	57.1
Original soil	.....	37.0	.....	25.5	.....	31.5	.....	45.5	.....	23.0	.....

[1] It should be stated that the addition of calcium carbonate exerts almost no effect on the nitrification of dried blood in this soil. A preliminary report on the above phases of this investigation has previously been issued (15).

Again, it was found that the lower concentrations of these materials were actively nitrified in every case; and when the concentration was increased, the percentage of nitrification decreased. One per cent dried blood was actively nitrified in every soil except that from Lark Ellen, but 2 per cent was toxic in each case. The percentage of dried blood nitrified was somewhat greater than that of bone meal; otherwise the degrees of nitrification of the different materials were similar. The results, therefore, are in harmony with those of the preceding series.

The preceding data show that each of the soils studied, representing quite a wide range of soil conditions, is capable of supporting active nitrification of dried blood, bone meal, or ammonium sulphate, provided these materials be added in low concentrations. They also indicate that the results obtained with the use of such high concentration of dried blood as 1 and 2 per cent, or 0.3 and 0.6 per cent of ammonium sulphate, do not form a reliable criterion upon which to base practical conclusions.

NITRIFICATION AT DIFFERENT DEPTHS AS AFFECTED BY CONCENTRATION

As already stated, differences of opinion are held regarding nitrification in the substrata of semiarid soils. The following data are of interest in this connection. The soil used was taken from an orange grove near Woodlake, in Tulare County. It is a dark-colored clay loam, high in organic matter. The subsoil contains considerably less organic matter than the surface soil and closely resembles adobe. The samples were drawn in foot sections down to 5 feet in depth. Only a few concentrations of nitrogenous materials were employed, owing to the smallness of the samples. The incubation period was four weeks, as in the previous series. (Table IV).

TABLE IV.—*Nitrification in soil from different depths*

Materials added.	Nitrogen added per 100 gm. of soil.	First foot.		Second foot.		Third foot.		Fourth foot.		Fifth foot.	
		Nitric nitrogen found.	Percentage nitrified.	Nitric nitrogen found.	Percentage nitrified.	Nitric nitrogen found.	Percentage nitrified.	Nitric nitrogen found.	Percentage nitrified.	Nitric nitrogen found.	Percentage nitrified.
	Mgm.	*P.p.m.*		*P.p.m.*		*P.p.m.*		*P.p.m.*		*P.p.m.*	
None	0	60.0	.....	64.0	.....	46.0	.....	36.0	.....	35.0	.....
Dried blood, 1 per cent	132.0	32.0	0	2.6	0	1.8	0	0.1	0	9.2	0
Dried blood, 0.1 per cent	13.2	132.0	54.5	95.0	23.5	100.0	40.9	40.0	3.0	34.0	0
Ammonium sulphate, 0.0625 per cent	13.2	130.0	53.0	92.0	21.2	74.0	21.2	68.0	24.2	68.0	25.0
Original soil	.....	1.1	.....	4.5	.....	2.5	.....	3.6	.....	0.6	.....

Active nitrate formation took place in the check portions from each of the 5-foot sections studied, showing that the nitrifying organisms are not only present down to 5 feet in depth but that the chemical, physical, and biological conditions ensuing in the samples were favorable for nitri-

fication. The results show, furthermore, that 1 per cent of dried blood may be an excessive concentration, even in a highly organic soil; less nitrate was formed in the samples for each foot where 1 per cent of dried blood had been added than in the control portions.

A concentration of 0.1 per cent of dried blood, or an equivalent amount of nitrogen in the form of ammonium sulphate, underwent vigorous and practically equal nitrification in the soil from the first foot and was also actively nitrified in the subsoils from the second and third feet. Ammonium sulphate likewise underwent considerable nitrification in the samples from the fourth and fifth feet; but the amounts of nitrate produced with a 0.1 per cent concentration of dried blood in soil from these depths were approximately the same as in the checks, indicating that a concentration of 0.1 per cent of dried blood may be excessive.

Considering the fact that nitrification took place in the check portions and where ammonium sulphate was added, the conclusion seems warranted that the subsoil from this orchard at least possesses the potential capacity of producing nitrates down to a depth of 5 feet.

However, the writer does not consider it safe to conclude from the preceding data that active nitrification takes place in the field in the subsoils of the orchard from which the above sample was drawn, since much more thorough aeration took place after the samples were drawn than ordinarily takes place in the subsoil *in situ*.

The results, as a whole, again emphasize the importance of employing low concentrations of nitrogenous materials and show that the inability to nitrify a concentration of 1 per cent of dried blood is not confined to humus-poor soil, as suggested by Lipman and Burgess (24).

EFFECTS OF ALKALI SALTS ON NITRIFICATION AS MODIFIED BY THE CONCENTRATION OF NITROGENOUS MATERIALS

One of the most important soil questions in the semiarid region relates to the effects of alkali salts, particularly the carbonate, chlorid, and sulphate of sodium. As already stated, Lipman and his coworkers (17, 18, 19, 22) have devoted considerable study to the biochemical effects of these salts. But the conclusions which were drawn relative to nitrification were based on the effects produced with a concentration of 1 or 2 per cent of dried blood. In the light of the results presented above, it becomes a matter of interest to study the effects of alkali salts with the use of varying concentrations of nitrogenous materials.

The soils used were drawn from the check and manured plots; the required amounts of the salts were added in solution after the dried blood or ammonium sulphate had previously been mixed with the soil. The same percentage of moisture and an incubation period of four weeks were employed, as in the previous series. Table V gives the results of this series.

TABLE V.—*Effect of alkali salts on the nitrification of dried blood and ammonium sulphate*

Alkali salt added.	Nitric nitrogen (per million).					
	Control plot.			Manured plot.		
	0.1 per cent of dried blood.	0.0625 per cent of ammonium sulphate.	0.15 per cent of ammonium sulphate.	1.0 per cent of dried blood.	0.1 per cent of dried blood.	0.15 per cent of ammonium sulphate.
None	108. 0	98. 0	89. 0	172. 0	106. 0	170. 0
Sodium carbonate:						
0.05 per cent	.....	.....	56. 0	31. 0	108. 0	129. 0
0.1 per cent	104. 0	160. 0	33. 5	19. 0	102. 0	62. 0
0.5 per cent	1. 5	1. 9	1. 1	7. 6	[a] 110. 0	5. 6
Sodium sulphate:						
0.1 per cent	115. 0	96. 0	60. 0	296. 0	103. 0	174. 0
0.5 per cent	98. 0	95. 0	41. 0	48. 0	102. 0	134. 0

[a] 0.4 per cent of sodium carbonate was used in this case.

Considering the results from the control plot, it is interesting to note that 0.1 per cent of sodium carbonate produced no effect upon the nitrification of a concentration of 0.1 per cent of dried blood, was distinctly toxic to the nitrification of a concentration of 0.15 per cent of ammonium sulphate, and markedly stimulating to the nitrification of a concentration of 0.0625 per cent of ammonium sulphate. A concentration of 0.5 per cent of sodium carbonate was toxic in all cases.[1]

With a 1 per cent concentration of dried blood in the soil from the manured plot, the addition of a concentration of 0.05 per cent of sodium carbonate was quite toxic to nitrification, causing a reduction in the yield of the nitrate from 172 to 31 p. p. m. A 0.1 per cent concentration of sodium carbonate was still more toxic, while a concentration of 0.5 per cent totally inhibited nitrification. (The original soil contained 6.7 p. p. m.) With the use of 0.1 per cent dried blood no effects were produced by any of the concentrations of sodium carbonate employed. With the use of a concentration of 0.15 per cent of ammonium sulphate the addition of 0.05 or 0.1 per cent sodium carbonate retarded nitrification considerably, especially in the case of the latter, but not so markedly as was found in the case of 1 per cent dried blood.

The addition of a concentration of 0.1 per cent of sodium sulphate was without effect on the nitrification of 0.1 per cent dried blood or an equivalent amount of ammonium sulphate in the control plot, and upon the nitrification of concentrations of 0.1 per cent of dried blood or 0.15 per cent of ammonium sulphate in the manured plot; but it produced marked stimulation with 1 per cent dried blood in the manured plot and was toxic with 0.15 per cent ammonium sulphate in the control plot. A concentration of 0.5 per cent of sodium sulphate was somewhat toxic with 1

[1] The chemistry of the action of sodium carbonate and other sodium salts on this soil will be discussed in a subsequent paper. Suffice it to say that considerable light has been thrown on the above results from a study of the pure chemistry involved.

per cent dried blood and 0.15 per cent ammonium sulphate; but it produced no effects on the nitrification of a concentration of 0.1 per cent of dried blood.

With one exception it is noteworthy that the effects produced by either sodium carbonate or sodium sulphate were quite similar when equal amounts of nitrogen in the form of dried blood and ammonium sulphate were employed in low concentrations.

The above results are in harmony with those of Lipman (18) in showing that sodium carbonate is extremely toxic to the nitrification of a high concentration of dried blood and far more toxic than sodium sulphate.

NITRIFICATION DURING DIFFERENT LENGTHS OF TIME

In the preceding studies the samples were incubated for four weeks, and, as already stated, conclusions on the relative rates of nitrification of different materials and in different soils have frequently been drawn from data obtained in this way. In the light of the preceding results it becomes a matter of interest to study nitrate formation at different intervals of time. In a preliminary study with the use of 1 per cent of dried blood in soil from the control plot it was found that no nitrification took place during a period of 68 days. In another series with the use of the same soil the incubation period was extended to 105 days, with the same result. With still other soils in which a concentration of 1 per cent of dried blood failed to be nitrified in four weeks, it has been found, however, that active nitrification may set in later, and in some cases eventually becomes quite as active as in soils which have the power of nitrifying 1 per cent vigorously within four weeks.

For the purpose of studying nitrification progressively with low concentrations of materials, 2,000 gm. of the fresh soil from the check and manured plots were kept in large jars. Dried blood and ammonium sulphate were added in quantities supplying 10 mgm. of actual nitrogen per 100 gm. of soil. The mositure content was brought up to 15 per cent and maintained near this point by the occasional addition of distilled water as evaporation took place. The soils were incubated as before. One-hundred-gm. portions were withdrawn at intervals and the nitrate determined, as shown in Table VI.

TABLE VI.—*Nitrification during different intervals of time*

Soil.	Nitrogenous materials added.	Nitric nitrogen (parts per million).						
		Original soil.	After 4 days.	After 7 days.	After 9 days.	After 15 days.	After 31 days.	After 94 days.
Control plot...	None.....	1.2	4.0	7.0	7.4	9.0	7.5	16.5
Manured plot...	.....do.....	4.9	9.8	10.0	12.0	13.2	14.0	23.0
Control plot...	Dried blood.....	1.2	2.2	10.4	33.5	66.0	60.0	72.0
Manured plot...	.....do.....	4.9	10.4	44.0	58.0	73.0	64.0	64.0
Control plot...	Ammonium sulphate.	1.2	4.4	16.5	37.0	65.0	76.0	88.0
Manured plot...	.....do.....	4.9	14.4	60.0	72.0	96.0	96.0	96.0

The above data show that nitrification set in within the first four days and continued in the untreated portions throughout the 94 days of the experiment. When allowance is made for the nitrate originally present, it will be seen that almost as active nitrification took place in the untreated soil from the control plot as in that from the manured plot. But with the addition of 10 mgm. of nitrogen in the form of dried blood, the more active nitrification took place during the first nine days in the soil from the manured plot. After this time nitrate formation took place the more vigorously in the soil from the control plot.

Ammonium sulphate was most actively nitrified in the manured soil during the first 31 days. After this time the rate in the control plot exceeded that in the manured plot. At every time interval, with the exception of the 15-day period, ammonium sulphate was found to undergo more active nitrification than dried blood.

If the rates of nitrification in the two soils be compared on the basis of the data obtained upon the ninth day,[1] it would seem reasonable to conclude that the manured plot is capable of supporting more active nitrification of either dried blood or ammonium sulphate than the check plot. If a later period be chosen the inference seems equally reasonable that the two soils are about equal in ability to nitrify dried blood. The data obtained from the untreated portions, however, would seem to indicate that the floras of the two soils are quite similar, so far as their ability to produce nitrate is concerned. In a subsequent paper this point will be more fully discussed.

The preceding data strongly emphasize the importance of studying the formation of nitrates in laboratory studies during different intervals of time and in the presence of varying concentrations of different nitrogenous materials. Just as different concentrations of nitrogenous materials, as already stated, may lead to widely different conclusions, the above results show that almost any conclusion may be drawn regarding the relative rates of nitrification of dried blood and ammonium sulphate in a given soil or of dried blood in different soils, provided the incubation periods be carefully chosen.

ACCUMULATION OF NITRITES IN LABORATORY EXPERIMENTS ON NITRIFICATION

From the classical experiments of Winogradsky it is generally considered that nitrification proper begins with ammonia and takes place in two stages, each stage being brought about by a different set of bacteria. The nitrite bacteria oxidize the ammonia to nitrous acid, and the nitrate bacteria complete the oxidation to nitric acid. In field soils, however, the activity of the latter is usually sufficiently great to complete the oxidation of nitrite almost, if not quite, as fast as it is formed. Hence, nitrite rarely accumulates in notable amounts in arable soils.

[1] Such comparisons have previously been made (8, 27) upon the basis of a 10-day incubation period.

However, nitrite may accumulate to a considerable extent under poorly aerated conditions, especially when artificial applications of nitrate fertilizers are made, but under such conditions it is highly probable that the nitrite is formed in part at least through the reduction of nitrates rather than from the incomplete oxidation of ammonia. The writer (12) has shown, for example, that the application of sodium nitrate to rice soils immediately preceding or during the time of submergence may result in an accumulation of considerable amounts of nitrite. The addition of large amounts of carbohydrates may also bring about a similar reduction of nitrates, even under aerobic conditions. In general, it may be said that the accumulation of notable amounts of nitrite in soils is an indication of the existence of unfavorable soil conditions.

Notable amounts of nitrite have previously been found in laboratory incubation experiments on nitrification. In experiments with the use of asparagin Withers (35) found considerable amounts of nitrite in certain soils in North Carolina, while only slight nitrate formation took place. On the other hand, ammonium sulphate was oxidized to nitrate without the accumulation of more than a trace of nitrite. In sterilized portions of this soil, which were later exposed to reinoculation, notable amounts of nitrite were formed within four weeks' time from both asparagin and ammonium sulphate, but practically no nitrate was formed from either. The amounts of nitrogenous materials used in these experiments were not stated.

Sackett (28) also found considerable amounts of nitrite in laboratory experiments. He used 100 mgm. of actual nitrogen in the form of ammonium sulphate, ammonium chlorid, ammonium carbonate, and dried blood per 100 gm. of soil, which corresponds, in the case of ammonium sulphate, to a concentration of about 0.5 per cent, and in that of dried blood approximately to 0.75 per cent. The incubation period was six weeks. It is notable that in certain soils he found that nitrite formation took place much more rapidly than nitrate formation, and in other soils there was evidence of nitrite formation through the reduction of nitrate. In the control portions to which no nitrogenous materials were added the concentrations of nitrite did not amount to more than 1 to 2 p. p. m. It is probable that the results obtained by Sackett would have been greatly different had he employed a lower concentration of the nitrogenous materials.

The writer (13) has also previously found considerable amounts of nitrite in laboratory experiments with the use of excessive amounts of magnesium carbonate. In these experiments a concentration of 2 per cent of dried blood was employed with the light, sandy soil from Anaheim, Cal. In discussing this point it was tentatively suggested that the nitrite found arose from the reduction of nitrate, and that the magnesium carbonate was more toxic to the nitrifying bacteria than to the denitrifiers. In the light of evidence obtained more recently it seems

more probable, however, that the magnesium carbonate in low concentrations was toxic to the nitrate formers but not to the nitrite formers, whereas in still higher concentrations it was toxic to both groups.

In the course of some studies on the effects of concentration on the nitrification of ammonium carbonate it was observed that notable amounts of nitrite began to accumulate as the concentration was increased above 15 mgm. of nitrogen per 100 gm. of soil; with a concentration of 30 mgm. the nitrite content, after four weeks' incubation, was found to be 268.5 p. p. m., while at the same time no nitrate was formed. From these observations it would seem that the nitrate bacteria are more sensitive to high concentrations of ammonium carbonate than the nitrite group, as has been definitely shown to be the case by Boullanger and Massol (4).

The effects on nitrite accumulation brought about by the concentration of different nitrogenous substances and in different soils, the effects produced by the addition of alkali salts, organic matter, etc., have been studied at varying intervals of time. The full data will be presented in a later paper. Briefly, it may be stated that not more than a few tenths p. p. m. of nitrite have been found where low concentrations of nitrogenous materials have been used, but that as the conditions become increasingly abnormal, either through the use of excessive amounts of nitrogenous substances, the addition of alkali salts, or by other means, a point is usually reached where nitrite formation proceeds more vigorously than nitrate formation, with a consequent accumulation of considerable amounts of nitrite. In addition, it has been found that under certain conditions nitrite formation may proceed vigorously without nitrate formation taking place at all, even in a soil where the nitrate bacteria are present in abundance.

The occurrence of notable amounts of nitrite necessitates some departure from the methods usually employed in the determination of nitrate in soils. As already stated, the results obtained by the phenol-disulphonic-acid method were found to agree closely with those obtained by the aluminum-reduction method except where high concentrations of nitrogenous materials had been employed. In such cases the reduction method frequently gave much higher results.[1] As shown below, the use of the reduction method effects a conversion of nitrite into ammonia, just as is the case with nitrates; and consequently the results found represent the total of the nitrite and nitrate nitrogen present, although it is recorded as nitrate.

If a solution containing nitrite is evaporated and the residue then treated with the phenol-disulphonic-acid reagent, small amounts of nitrite may also be converted into nitrate, thus introducing a slight error.

After considerable experimentation the method adopted for the determination of nitrate in the presence of nitrite was as follows: The water

[1] As shown by Allen (1), certain soluble organic forms of nitrogen also become reduced to ammonia under the conditions employed in this method.

solution of the soil was made up as usual. To an aliquot portion, 10 c. c. of a 1 per cent solution of ammonium sulphate was added, then evaporated on the water bath, and the determination completed as usual with the phenol-disulphonic-acid method. During the evaporation the ammonium sulphate brings about complete decomposition of the nitrite through the formation of ammonium nitrite, which decomposes at the temperature employed.[1] The nitrite was determined by the Griess-Ilosvay method.

The following data (Table VII) will show the wide range of results obtained by the use of different methods:

TABLE VII.—*Effects of nitrite on the determination of nitrate (in parts per million)*

	Nitrite nitrogen.	Nitrate nitrogen by modified colorometric method.	Nitrate nitrogen by the usual colorometric method.	Nitrate nitrogen by aluminum reduction method.
Soil plus 1 per cent of dried blood incubated for 46 days	275	22	30	283

The above data show that nitrite becomes reduced to ammonia under the conditions employed in the aluminum reduction method. It is reasonable to infer, therefore, that unless allowance be made for the nitrite present the results obtained by the reduction method from incubations with high concentrations of nitrogenous materials will represent the total nitrite and nitrate present rather than the nitrate only (22).

It has been found that with the use of 1 per cent of dried blood nitrites may accumulate in large amounts in soils of various types and that the nitrite may persist without undergoing further oxidation, at least for a period of 105 days, as shown in Table VIII.

TABLE VIII.—*Accumulation of nitrite as affected by concentration (in parts per million)*

Soil.	Original soil.		After 28 days.		After 42 days.		After 56 days.		After 71 days.		After 105 days.	
	Nitrite nitrogen.	Nitrate nitrogen.	Nitrite nitrogen.	Nitrate nitrogen.	Nitrite nitrogen.	Nitrate nitrogen.	Nitrite nitrogen.	Nitrate nitrogen.	Nitrite nitrogen.	Nitrate nitrogen.	Nitrite nitrogen.	Nitrate nitrogen.
Control plot untreated	0	1.4	0	12.0	0	11.2	0	12	0	15	0	18
Control plot plus 0.0625 per cent of dried blood	0	1.4	Trace.	60.0	0	70.0	0	70	0	67	0	68
Control plot plus 1 per cent of dried blood	0	1.4	20	19.5	87.5	26.0	150	19	150	24	265	29
Manured plot untreated	0	3.2	0	14.0	0	17.0	0	17	0	26	0	25
Manured plot plus 0.0625 per cent of dried blood	0	3.2	Trace.	50.0	0	60.0	0	72	0	74	0	70
Manured plot plus 1 per cent of dried blood	0	3.2	107	160.0	56.0	272.0	75	300	0	465	0	416

[1] This procedure was suggested by the method formerly employed for the determination of nitrate in the presence of nitrite by Frankland (6).

The above shows that large amounts of nitrite may accumulate when high concentration of dried blood have been used, but with a low concentration such is not the case. It is noteworthy that high concentration of other nitrogenous materials, such as bone meal, ammonium sulphate, and ammonium carbonate, all have been found to promote the accumulation of large amounts of nitrite in incubation studies.

Alkali salts also exert marked effects upon the accumulation of nitrites as shown by Table IX.

TABLE IX.—*Effects of sodium carbonate on the accumulation of nitrite*

Nitrogenous material added.	Sodium carbonate added.	After two weeks.		After four weeks.	
		Nitrite nitrogen.	Nitrate nitrogen.	Nitrite nitrogen.	Nitrate nitrogen.
	Per cent.	*P. p. m.*	*P. p. m.*	*P. p. m.*	*P. p. m.*
None	None.	0	16.2	0	48.0
0.1 per cent of dried blood	do	0	84.0	0	110.0
Do	0.1	Trace.	86.0	0	100.0
Do	0.25	25.0	19.2	25.0	102.0
Do	0.5	Trace.	1.5	0	2.0
0.0625 per cent of ammonium sulphate	None.	0	68.0	0	104.0
Do	0.1	Trace.	106.0	0	160.0
Do	0.25	62.5	10.0	93.8	79.0
Do	0.5	1.7	1.7	0.5	1.9

Not more than a mere trace of nitrite was found where a concentration of 0.1 per cent of sodium carbonate had been added, and no effect was produced on nitrate formation; but considerably greater amounts of nitrite than nitrate occurred after two weeks' incubation where a concentration of 0.25 per cent of sodium carbonate had been added. However, after four weeks most of the nitrite formed from dried blood had become oxidized to nitrate; while in the case of ammonium sulphate, the concentration of nitrite after four weeks still exceeded that of nitrate. The addition of 0.5 per cent of sodium carbonate entirely inhibited the formation of either nitrite or nitrate.

It has been found that a concentration of from 30 to 40 mgm. of nitrogen in the form of sodium nitrite per 100 gm. of soil entirely inhibits the formation of nitrate in the soil from the experimental plots. With lower concentrations the nitrite was completely oxidized in four weeks' time. These results taken in connection with the preceding indicate that when abnormal soil conditions are brought about, the concentration of nitrite produced in the oxidation of nitrogenous materials may become so high as in itself to inhibit nitrate formation.

CONCLUSIONS

In the preceding investigations it has been shown that the amounts of nitrate formed from dried blood, bone meal, or ammonium sulphate during four weeks' incubation varied enormously when different concentrations were employed. This is true in regard both to the absolute amount

of nitrate formed and the percentage of the nitrogen added that was nitrified.

When 1 per cent of dried blood was used, the nitrifying activity was found to be feeble or even negative in certain soils in which 1 per cent of bone meal and 0.2 to 0.3 per cent of ammonium sulphate underwent active nitrification, as was previously found by Lipman and Burgess (24). However, when low concentrations of dried blood were employed, such as are used in the field, active nitrification took place in every case; and when equal amounts of actual nitrogen were added, it was found that the yields of nitrate were quite similar, whether the nitrate had been derived from dried blood, bone meal, or ammonium sulphate. High concentrations of bone meal with a nitrogen content corresponding to that furnished by 1 per cent of dried blood were also toxic to nitrification, very much as was the case with 1 per cent of dried blood.

Experiments were made with widely different types of soil from a number of localities in southern California. It was found that the inability to nitrify 1 per cent of dried blood is not confined to any one type of soil nor to soils low in organic matter. The results as a whole seem to warrant the conclusion, however, that the soils of southern California in general are capable of supporting active nitrification of dried blood, provided it be added in concentrations corresponding to field practice.

It was found that the effects produced by the addition of alkali salts varied greatly when different concentrations of nitrogenous materials were employed. In a given soil a concentration of 0.05 per cent of sodium carbonate was distinctly toxic to the nitrification of 1 per cent of dried blood, while as high a concentration as 0.4 per cent produced no effects on the nitrification of 0.1 per cent of dried blood. Likewise, 0.1 per cent of sodium carbonate was toxic to the nitrification of 0.15 per cent of ammonium sulphate, and markedly stimulating when 0.0625 per cent of ammonium sulphate was used. Similar statements may be made with regard to the effects of sodium sulphate.

The results also show that widely different conclusions may be drawn from laboratory experiments when different periods of incubation are used.

Nitrites were found to accumulate in large amounts where excessive amounts of nitrogenous materials were employed. In some cases the nitrite content greatly exceeded the nitrate content after an incubation period of several weeks. Likewise, the addition of alkali salts may suppress nitrate formation, while at the same time permitting nitrite formation to proceed actively.

It is necessary to make allowance for the nitrite present in the determination of nitrate by the aluminum reduction or phenol-disulphonic-acid methods, but the error introduced by nitrite is far greater with the former method than with the latter.

It is not intended to give the impression from the above that all nitrogenous materials will undergo nitrification at equal rates when

present in low concentrations. It is recognized that different organic fertilizers undergo biochemical decomposition in varying degrees in a given soil, and this for a number of reasons, some of which will be discussed in a later paper. The writer holds, however, that the methods now employed by many students of nitrification, in which high concentrations of nitrogenous materials are added and the nitrate determined at a fixed interval of time, are not only unsatisfactory but that the results thus obtained are likely to be more misleading than informing.

In the light of the results obtained in this investigation, it seems highly probable that at least some of the peculiarities that have been noted in previous nitrification studies will be found to disappear under the more rational procedure of studying the activities of the organisms in an environment as nearly similar to that of the field as possible. The writer, while criticizing the methods in common use, freely admits that some of the conclusions previously drawn by him from studies with Hawaiian soils are open to serious question because of the methods employed (14).

The nitrate merely represents one of the end products formed; and in the case of an organic substance the intermediate products that are produced may, either directly or indirectly through the effect upon other organisms, exert much influence upon the oxidation of ammonia. In the presence of large amounts of materials it is highly probable that the relations of the different groups of organisms present become greatly changed, with a consequent effect on the oxidizing activity of the nitrifying organisms.

It is, of course, a matter of scientific interest that certain soils are capable of supporting active nitrification of 1 per cent of dried blood, while others are not, and the reasons underlying these differences are matters deserving further study, but so far as the practical side of nitrification is concerned the writer holds that laboratory experiments should be conducted under conditions as nearly comparable with those that obtain in the field as possible, and that at the present time nothing more than scientific interest can safely be attached to the results obtained with the use of such abnormally high concentrations of nitrogenous materials as are commonly used in laboratory experiments on this subject.

Many American bacteriologists have apparently accepted the conclusions of Stevens and Withers (29, 30) and have multiplied laboratory tests in a conventional way without seriously questioning the method. The result has been that the practical aspects of nitrification studies have become extremely empirical. While it has frequently been stated that nitrification in the laboratory is not strictly comparable with that in the field, the conditions obtaining in the nitrification of 1 per cent dried blood in the laboratory have been referred to as optimum conditions (27). The preceding data indicate, however, that such may be far from the case. The writer thoroughly agrees with the position taken by Löhnis and Green (25) and Allen and Bonazzi (2) in their recent discussions of this subject.

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FACTORS AFFECTING THE EVAPORATION OF MOISTURE FROM THE SOIL[1]

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INTRODUCTION

The importance of soil moisture in crop production is well understood. No plant can grow unless moisture is present to help make food available and furnish the water necessary to carry on regular plant functions. In arid regions the growth of crops is limited more by a lack of moisture than by any other factor, and even in regions of high rainfall crop yields are often materially reduced by droughts.

In sections where only a small amount of rain falls, practically all that sinks into the soil returns to the surface and is evaporated directly or passes through plants, from which it is evaporated. In humid regions also, where some of the soil moisture percolates to great depths, there is considerable loss by evaporation from the surface of the soil.

Moisture evaporated from the soil is completely lost and is of no value to crops; hence, it is important to reduce evaporation to a minimum, particularly where the supply of moisture is limited. The best condition would be to have no evaporation of moisture except that passing through the plant and assisting in its functions. Any information, therefore, that will lead to a better understanding of the factors involved in evaporation and a fuller knowledge of methods of controlling these factors will be of considerable practical importance as well as scientific interest.

Surface losses are due to two factors: (1) Capillarity, by which the moisture is brought to the surface, and (2) evaporation. In many of the soil-moisture studies that have been made these two factors have not been clearly separated, but have been considered together in determining loss. This has led to considerable confusion, since a difference in two losses might, in one case, be due to a difference in the rate at which moisture was supplied to the surface by capillarity and, in another case, to the evaporation factors.

In the experiments reported in this paper an attempt has been made to eliminate the factor of capillarity and to confine the studies entirely to evaporation in order to determine, as nearly as possible, the effect of a number of the factors involved in the evaporation of moisture from the soil.

[1] The writers wish to acknowledge their indebtedness to Messrs. George Stewart and N. I. Butt, of the Utah Experiment Station, for their assistance with certain experiments and in preparing this paper for publication.

Journal of Agricultural Research,
Dept. of Agriculture, Washington, D. C.
gj

Vol. VII, No. 10
Dec. 4, 1916
Utah—4

REVIEW OF THE LITERATURE

Considerable work has been done on various phases of the evaporation problem. One of the important factors influencing water losses is the wetness of the soil, or the initial percentage.

Widtsoe (19, p. 35, Table 20)[1] gives the results of four years' experimental work, as shown in Table I.

TABLE I.—*Total evaporation of water from bare College loam*

Moisture.	Loss in pounds per square foot.				
	1902	1903	1904	1905	Average.
Per cent.					
10	9	32	9	16	16
15	23	.....	10	30	21
20	51	80	38	69	60

Loss increased with the percentage of water up to 20 per cent, which was the highest degree of wetness used. He (19) says: "The evaporation of water from bare soils increased with the increased saturation of the soil. The increase in loss was usually much larger than the increase in saturation. In another treatise (20) he found that "the wetter the soil at the surface, the more rapid is the evaporation of water from it."

This is confirmed by Whitney and Cameron (18) and by Fortier (5). In Whitney and Cameron's work, 26 per cent was the highest humidity, that being used in but one set of experiments. Fortier's highest percentage of water was 17.5. In his conclusions he says, "The rate of evaporation from soils varies directly with the amount of moisture in the top layer."

The work of Cameron and Gallagher (3, p. 45-49) indicates that, after a certain wetness is reached, there is little if any increase in water loss. In their work the soils of different degrees of wetness were placed over sulphuric acid of different concentrations in order to control the humidity. Over 95 per cent sulphuric acid in desiccators, Podunk fine sandy loam gave the most rapid loss by evaporation up to 4 per cent moisture, with a very slight increase in loss up to 28 per cent. Miami black clay loam lost most rapidly up to 22 per cent, with a small increase to 41 per cent, where the loss was highest.

The color of the soil is claimed by King (10) to affect evaporation greatly, since the darker the soil the more heat it absorbs and radiates. He found that the rise in temperature, due to the darker color, is the important factor.

Concerning winds, King (9, p. 16) shows that up to 300 feet from woods the loss gradually increased with the distance. He (11) gives the following

[1] Reference is made by number to "Literature cited," p. 460-461.

data on evaporation for an hour from a wet soil with a surface of 27 square inches:

20 feet from hedgerow the evaporation was 10.3 c. c.
150 feet from hedgerow the evaporation was 12.5 c. c.
300 feet from hedgerow the evaporation was 13.4 c. c.

At 300 feet the evaporation was 30 per cent greater than at 20 feet and 6.7 per cent greater than at 150 feet, due largely to the vessels closer to the hedge having protection from the wind.

McDonald (12) gives this terse summary:

> Evaporation depends upon the temperature of the evaporating surface, the dryness of the air, and the velocity of the wind. The hotter the day, the greater the evaporation; the drier, the greater the evaporation—the ceaseless sucking up of moisture.

Bowie (1) claims that loss due to wind is caused by the more intimate contact of the air with the moist soil surface. He says:

> With average wind velocities of from 2.4 to 4.0 miles an hour, and with an average water temperature of 70 F., the increased evaporation rate due to wind was about 0.5 per cent a day for each mile of wind.

Payne (13), in giving the advantage of windbreaks in retarding evaporation, shows that a sod wall 4 feet high and 20 feet long, running east and west, reduces the loss from buckets placed in the ground level with the field. On the north side, buckets 1, 3, 5, 7, and 10 rods distant lost in 62 days moisture the equivalent of 677, 633, 700, 703, and 712 tons to the acre, respectively; on the south side, buckets 1, 3, 5, 7, and 8 rods distant gave losses of 647, 686, 738, 764, and 761 tons to the acre, respectively.

In work done by Principi (14) the conclusions reached were—

> That evaporation is most rapid from the materials which have the largest pore spaces, and that it remains almost the same whether it arises from a free water surface or from thin films covering the particles of wet material.

Woolny (21) claims that capillarity ceases when the diameter of the particles is more than 2 mm. and that it varies with smaller particles in proportion to their fineness—the finer the particles, the greater the lifting power, but the slower the movement.

In regard to moisture movement through a column of dry soil not in direct contact with the moisture but with a saturated atmosphere between, Buckingham (2, p. 9–18) says that moisture escapes probably by pure diffusion and that the loss in this way is proportional to the square of the porosity, following the same law as the diffusion of air and carbon-dioxid gas through soils.

Whitney and Cameron (18) showed that loams over a saturated atmosphere gave a greater diffusion of moisture through the pore spaces than through those of clay.

Fortier (5) shows, in the measurement of losses from water surfaces kept at different temperature, that reducing the temperature from 88° to 80.4° F. lessened evaporation 20 per cent; reducing it to 73.5° decreased evaporation 40 per cent; to 61.3° decreased it to 67 per cent; and to 53.4° reduced it to 85 per cent.

Shade, which is a great protection from heat, aids in preventing evaporation. Seelhorst (16) shows that a loam soil shaded by dry rye plants evaporated 13.9 per cent less of the rainfall than the same kind of soil unshaded.

Widtsoe's (20) work on the influence of shade on evaporation gives a loss of 22 pounds to the square foot as against 32 pounds for the unshaded portion; that is, there was 29 per cent greater loss in sunshine than in shade.

Fortier (6) shows that in actual experiments on Mount Whitney evaporation decreased with altitude. The decrease was rather regular, except at the summit (14,502 feet), where greater evaporation took place than at either 10,000 or 12,000 feet.

According to Carpenter (4), diminished barometric pressure tends to increase evaporation to the extent of 14 per cent at 9,000 feet and 18 per cent at 10,000 feet over that at 5,000 feet.

Mulching the surface of the soil a few inches by stirring it is the most common practice in use for the preservation of moisture under field conditions. Ridgaway (15) shows that stirring the surface to depths of 2, 4, and 6 inches in different tanks once a week, with the water level kept 22 inches below the surface of the soil, lessened evaporation by 19, 23, and 45 per cent, respectively, of the amount lost from unstirred soil. His work also shows that where water is maintained at 6, 12, 18, and 22 inches below the surface, the losses were 95, 70, 45, and 35 per cent of evaporation from a free-water surface. This bears out Wollny's (21) statement that "if there is water underneath the soil the evaporation decreases as the distance between the surface of this water and that of the soil increases."

Fortier (7) sums up the results when dry soil coverings were substituted for stirred surfaces, as shown in Table II.

TABLE II.—*Losses by evaporation from soil surfaces variously treated*

Locality.	Loss from unmulched soil.	Loss from 3-inch mulch on soil.	Loss from 6-inch mulch on soil.	Loss from 9-inch mulch on soil.	Number of days run.
	Per cent.	*Per cent.*	*Per cent.*	*Per cent.*	
Davis, Cal.	35.00	14.71	5.94	0.78	32
Wenatchee, Wash.	14.33	3.98	2.10	1.06	21
Reno, Nev.	20.39	8.26	2.74	1.96	21
Average.	23.24	8.98	3.59	1.27	24.7

Using enough water to cover the surface with 3.14 inches, this author (5) found that no mulch gave a 0.72-inch loss; a 4-inch mulch, 0.21 inch; an 8-inch mulch, 0.1 inch; and a 10-inch mulch, 0.03 inch in 14 days—that is, the various mulches saved in 14 days 16.24, 19.75, and 21.97 per cent of the amount applied.

The advantage of deep furrows as a saving in furrow irrigation is brought out by Fortier (5). When the same quantities of water were applied to tanks in furrows 3, 6, 9, and 12 inches deep, he found that the losses at the end of 10 days were 25, 18, 10.2, and 6 per cent of the total water applied. The loss was most rapid for the first 2 days, and at the end of 5 days 77 per cent of the total loss for 10 days had occurred.

Widtsoe's (19) work shows that in the two treatments, sand containing 15 per cent, sandy loam containing 20 per cent, and Sanpete clay containing 25 per cent moisture, the average loss from the soil receiving surface irrigation was more than three times as great in the same length of time as that from a subirrigated soil. Fortier (5) shows that soil subirrigated 2 feet underground by pipes lost only 25 per cent as much water in 20 days as when irrigated by surface flooding.

According to Stigell (17), bacterial growth retards evaporation. He says that this is attributed to utilization of moisture by the organisms in their metabolic products, and reduction of the porosity of the medium by the metabolic products of the organisms. Hoffman's (8) work shows that after the bacteria in various culture media were added to the soil, evaporation was increased except in the case of manure. In drawing his conclusions he leads one to believe that if the experiment is of long duration the results may be reversed, due to the accumulation of carbon dioxid from the organism being taken up by the soil moisture, thereby increasing the surface tension of the water. Gelatin was found to retard evaporation and for that reason could not be used as a culture media.

EXPERIMENTAL WORK

INITIAL QUANTITY OF SOIL MOISTURE

To find, if possible, the specific influence of varying percentages of water in soils, a series of experiments was conducted at the Utah Agricultural Experiment Station in the years 1912 to 1916, inclusive. The preliminary tests show that evaporation losses increased rapidly with the increased wetness of the soil, or with the initial quantity. The latter studies were so arranged as to locate as many points of variation in the losses as possible.

Preliminary Study

Late in June, 1913, a study of the effect of initial quantity of moisture in the soil was begun. One hundred gm. of dry Greenville loam were put in small, weighed tin plates about 5 inches in diameter, and puddled

with water. The soil was then set aside to dry. When the condition of dryness was approached, the moisture was made up to the desired content. Twelve percentages—5, 7½, 10, 12½, 15, 20, 25, 30, 35, 40, 45, and 50—were run in triplicate. The pans were set on a table in a large laboratory room. Weighings were taken daily to the nearest one-tenth of 1 gm. and water was added to make up the loss. This experiment continued for 42 days, at the end of which time the losses were computed for each week and for the entire period. Table III gives the losses for each period.

TABLE III.—*Effect of initial quantity of water on evaporation*

Soil moisture.	Water evaporated.	Soil moisture.	Water evaporated.
Per cent.	*Gm.*	*Per cent.*	*Gm.*
5	96. 4	25	956. 1
7½	229. 2	30	1, 013. 3
10	363. 0	35	1, 048. 1
12½	484. 8	40	1, 074. 5
15	594. 0	45	1, 148. 1
20	822. 2	50	1, 185. 8

An examination of Table III shows that evaporation increased rapidly to about 20 per cent, less rapidly from 20 to 30 per cent, and slowly from 30 to 50 per cent.

LATER EXPERIMENTS

Various later studies were made with loam, sand, clay, and muck. The methods were similar to those used in the preliminary work, but the experiments were much more detailed and thorough. Most of the work was done in small tin plates and copper vessels 8 inches in diameter and 4 inches deep, though some tests were made in Petri dishes, some in long galvanized-iron tanks and some in deep cylindrical galvanized cans.

LOAM

The test with loam was conducted in the manner already described with 100 gm. of dry soil in tin plates. The percentages of moisture ran from hygroscopic water, which was about 1.8 per cent, to 50 per cent. The experiment was conducted for 13 days, from August 29 to September 12, the pans being made up to the original weight each day and shifted on the table to eliminate, in part, the influence of air currents.

A similar test was made during the winter in a steam-heated laboratory. All percentages from 1 to 40 were run in triplicate with 1 per cent intervals. Weighings were made each day and losses were considerably greater than those for the same number of days in the other trial. A possible explanation for this is that the laboratory under artificial heat

was slightly warmer and changed air much more frequently than in summer. The hygrometer showed somewhat lower humidity, but it could not show the influence of thorough ventilation.

The next study was made between June 4 and June 17, 1914. It was conducted in the same fashion, except that weighings were made twice daily, between 6 and 8 o'clock morning and evening. Four pans, instead of three, were used with each percentage from 1 to 50. The pans for 1 per cent gained up to about 1.8 per cent and then neither lost nor gained noticeably.

In addition to the pans containing wet soil, a pan of free water was exposed at each corner of the table on which the test was made. The two pans on the east and nearer the doors lost somewhat more than the two at the west end. All soils that approached saturation lost more than the free water. The losses from the 20 per cent pans were about equal to the average of those from the free-water pans.

An almost identical test was made in July which practically duplicated the former results. As 12 weighings were made, the length of this study was equivalent to 6 days.

These various experiments are combined in figure 1, which gives results for a total of 51 days with moisture up to 40 per cent, and 36 days with moisture up to 50 per cent. The curve for the 36-day results shows a rapid increase in evaporation with a higher initial percentage of moisture in the soil up to 7 or 8 per cent; then a less rapid increase up to 18 or 20 per cent, from which point the increase is small. In the tests continued for 51 days, the same general changes in the curve are noted, although the total loss is decidedly more than for the 36-day test.

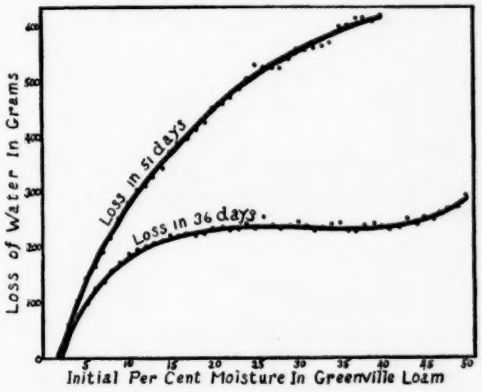

FIG. 1.—Evaporation from Greenville loam containing different initial percentages of moisture.

In some of the trials the free water lost more by evaporation than any of the wet soils, but usually there was a greater loss from soil which was completely saturated than from the free-water surface.

In each of these tests with Greenville loam, there seemed to be a number of more or less definite breaking points in the curves of loss. These indicate critical points where the moisture relations of the soil made rather sudden changes. A great deal of work will need to be done

under favorable conditions before these exact points of change can be determined.

In the summer of 1912 nine large galvanized-iron pans, or tanks, 5½ feet long by 1 foot wide by 3 inches deep were employed to give larger surfaces and deeper soil. The equivalent of 10 kgm. of dry Greenville loam was put into each tank and puddled with excess water to firm the soil and smooth its surface. Enough water in addition to the water already present—5.4 per cent—was added to make a series with 5 per cent intervals from 5.4 to 35.4 per cent. These tanks were set on the floor of the laboratory and were weighed on Monday, Wednesday, and Friday of each week. The losses were made up at the time of weighing. This study ran from June 12 to July 15, a period of 34 days.

The next year seven tanks were set up and run during the 81-day period from June 18 to September 6. This time 7.2 kgm. of Greenville loam, containing 2.6 per cent moisture, were used. Intervals of 5 per cent were again made, bringing the moisture content up to 7.6, 12.6, etc., as high as 37.6 per cent. Weighings were taken three times a week as in the first trial and water added to make up the evaporation loss. Table IV contains the results of the two trials.

TABLE IV.—*Effect of initial percentage of soil moisture on evaporation from Greenville loam in galvanized-iron tanks 5½ feet long and 1 foot wide*

1912		1913		Average of 2 tests.	
Moisture.	Loss in 34 days.	Moisture.	Loss in 34 days.	Average moisture.	Loss in 115 days.
Per cent.	*Gm.*	*Per cent.*	*Gm.*	*Per cent.*	*Gm.*
5.4	3,744	7.6	10,710	6.5	14,454
10.4	7,575	12.6	17,530	11.5	25,105
15.4	9,518	17.6	19,275	16.5	28,793
20.4	9,200	22.6	20,395	21.5	29,595
25.4	10,128	27.6	20,300	26.5	30,428
30.4	10,340	32.6	19,870	31.5	30,210
35.4	11,045	37.5	19,990	36.5	31,035

Table IV shows that the loss was rapid to 16.5 per cent and then slow. Of course, the wide intervals prevented locating exact points, but in general this test corroborates rather closely those already reported for loam.

SAND, CLAY, AND MUCK

During the period from December 26, 1913, to January 3, 1914, similar tests were made with sand, clay, and muck. One hundred gm., dry weight, of sand and clay and 50 gm. of dry muck were used in the same kind of tin plates as those used in the other trials. All percentages were run in triplicate, the sand for each percentage from 1 to 33, the clay for each percentage from 1 to 55, and the muck for each 20 per cent interval from

20 to 240 per cent. The muck consisted almost entirely of vegetable mold gathered from accumulated pockets in the brush swales of Logan River. It was known to have high water-holding capacity from previous experiments.

The pans were kept several inches back from the edge of the tables on which they rested. This almost entirely eliminated the effect of air currents which had, in previous tests, caused some variations in the rows of pans set close to the edge. The loss was made up each day after the weighing. The winter losses were much higher in this case than with the loam previously reported.

Figure 2 gives the results for sand and shows an increase in evaporation as the initial moisture is increased, up to 33 per cent. The most rapid increase is up to about 7 per cent. Above this point the increase in loss is not so great.

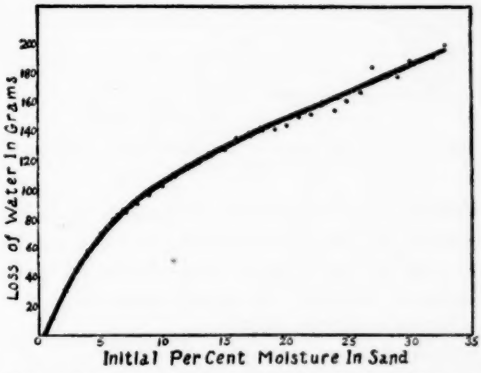

FIG. 2.—Evaporation from sand containing different initial percentages of moisture.

Figures 3 and 4 give the curves for clay and muck. The results for clay show a more gradual ascent in the curve, and a higher point before there is any break, than do the results for sand. This might have been expected from the great water-holding power of the clay. Muck with high percentages and differences at greater intervals produced about the same kind of curve as did loam.

More tests are necessary, however, to establish points as nearly exact as was done in the case of loam.

HUMIDITY OF THE AIR

To study the effect of a saturated atmosphere on evaporation, a set of wet soils in Petri dishes was placed in an air-tight copper germinator. Forty gm. of dry soil were put in each of these dishes, which were about 3 inches in diameter. Duplicate vessels were made up with soil for each 1 per cent from 1 to 35, and for each 2 per cent from 35 to 45 per cent of moisture. They were then set on the shelves of the germinator, which is a hollow box 22 inches wide, 37½ inches deep, and 47½ inches long. The whole was surrounded with a water jacket, except at the doors, which were made of two panes of glass inclosing a dead-air space about half an inch thick. The perforated copper shelves were covered with

cheesecloth and connected by a perpendicular wick to a water container on top. The wick kept all the cheesecloth covers saturated. To make sure no vapor escaped at the door, pieces of cloth kept constantly dripping were hung in front of the door. Tested thermometers showed throughout the experiment an almost constant temperature of 19.5° C., about one degree lower than that of the laboratory. Each day for 10 days the vessels were weighed to 0.01 gm. and made up by adding the water lost. The lower percentages, however, gained and were left at the wetness reached, which was about 7 per cent.

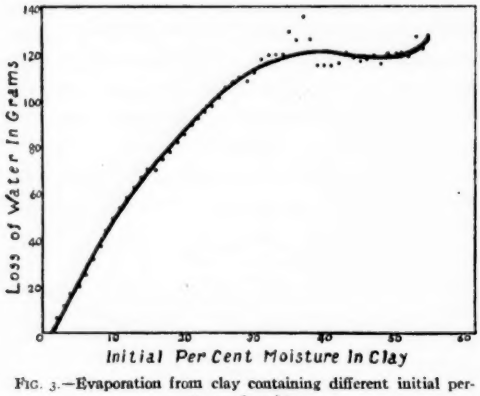

FIG. 3.—Evaporation from clay containing different initial percentages of moisture.

Fairly comparable with this test was another in which the same vessels, made up as before, were surrounded with cheesecloth 24 inches high to prevent drafts and to maintain a uniform temperature. Possible variations were eliminated by shifting the vessels in such a way that each occupied all sections of the cloth box some time during the 20 days of the experiment. The top was left open to permit vapor to escape upward. The relative humidity of the air was almost constantly at 76 per cent, whereas it was about 68 in the open laboratory. The temperature averaged 19° C. during the 20 days. Completely dried soil gained to 4 per cent, then remained constant. Weighings were made each day to the nearest 0.01 gm. and the losses made up as with the test in the germinator.

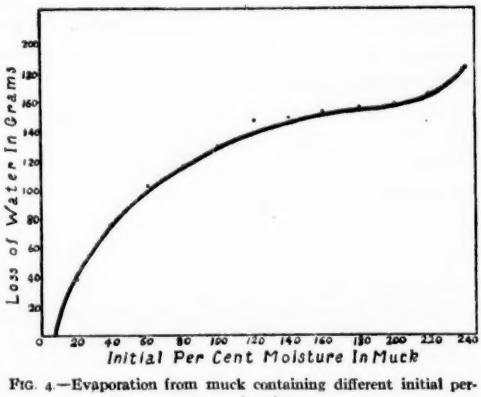

FIG. 4.—Evaporation from muck containing different initial percentages of moisture.

Figure 5 shows the losses for each 1 per cent in the saturated atmosphere of the germinator and for the slightly overmoist air of the cloth boxes.

Since the latter ran 20 days, the total losses have been divided by 2 in order to get the total loss for 10 days to make the figures comparable.

There is a decided difference in the results of the two experiments. The losses in the cloth boxes were nearly 20 times as great as those in the germinator, showing the enormous retarding effect of high humidity. Moreover, the open laboratory was somewhat drier and about one degree warmer than the air in the cloth boxes. No test was made in the open laboratory, but the losses would have been somewhat higher, since both a drier air and a higher temperature prevailed. This would, of course, further accentuate the already enormous differences.

WIND VELOCITY

As was suggested in the literature on wind velocity, King (9) has shown that vessels 20 feet from a windbreak lost 30 per cent less moisture by evaporation than vessels 30 feet distant. This was because the outer vessels were more exposed to air movement. Payne (13) shows nearly similar results, while Bowie (1) reports that with light winds and normal temperature there is an evaporation loss of 0.5 per cent for each mile of wind.

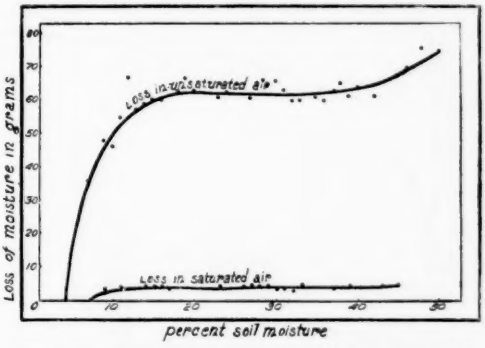

FIG. 5.—Loss of moisture from Petri dishes containing different percentages of soil moisture and kept in a saturated and unsaturated atmosphere.

In order to determine the effect of wind velocity on the rate of evaporation, a series of alleys 8½ inches wide and 70 inches long were arranged in such a way that the air could be made to pass through them at different velocities. The alleys were separated by oilcloth partitions 2 feet high; the air currents were made by electric fans placed in such positions that the desired velocities could be obtained. The velocity of air in each alley was measured with an anemometer placed at the end of the alley away from the fans.

The soils were contained in copper evaporimeters 6 inches in diameter. The loss each day was made up by adding water through a tube entering the evaporimeter at one side of the soil. In each alley there were five evaporimeters—one containing distilled water, one Greenville loam, and one each of quartz sand 0.25 mm., 0.5 mm., and 0.8 mm. in diameter.

Two tests were made in the experiment, one running continuously for 16 days with three wind velocities and another running continuously for

20 days with seven velocities. In each case there was an alley where the air was kept quiet. The combined results of the two tests are shown in figure 6. There is a rapid increase in evaporation with increased wind velocity at first; but after a velocity of about 10 miles per hour is reached, the increase in evaporation is slight. The water loss with the highest velocity was over four times that of the calm for the 16-day trial and nearly six times that of the calm in the 20-day test.

SUNSHINE

The general effect of sunshine in increasing the evaporation of soil moisture has long been known. The work of Seelhorst and Widtsoe on this subject has already been reviewed. In order to get more data an experiment was begun in the summer of 1913 at the Utah Agricultural Experiment Station. A spot on the college lawn just west of the main building was selected, because it was level and exposed to sunshine most of the day.

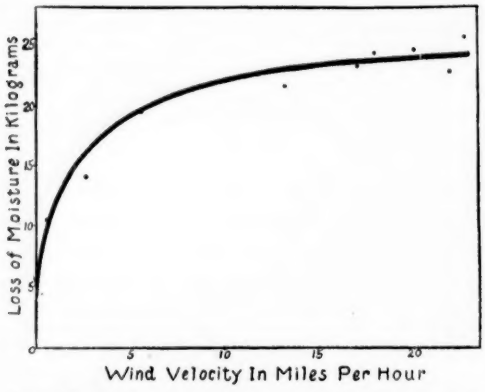

FIG. 6.—Evaporation of water from wet soils with different wind velocities.

Small tin plates containing 100 gm. dry weight of Greenville loam were prepared by puddling the soil and then drying, in order to get uniformity. They were then made up to the desired degree of wetness—5, 10, 15, 20, and 25 per cent, respectively. Each treatment was run in triplicate, making 15 pans to the set. One set was exposed to open sunshine, another was placed under a shade of cheesecloth 8 inches above the soil, and a third was shaded by a tight board cover also 8 inches above the soil. In each case the pans of soil were placed on a floor of boards and air was allowed to circulate freely over the soil beneath the cover.

The pans were each morning made up in the laboratory to the proper wetness and carried outside. Temperature readings were taken in the morning when the pans were carried out by laying a tested thermometer for a few minutes between the pans. A reading was taken at noon and another in the afternoon just before the pans were carried back into the laboratory. Another weighing of the pans showed the recorded loss due to evaporation. The pans were then left over night to be made up in the morning before placing outside.

Table V shows the average temperature for morning, noon, and afternoon. It is worth noting that the shade caused a reduction in temperature, complete shade causing a greater reduction than part shade.

TABLE V.—*Effect of shading on temperature and evaporation; temperature (° C.) average for 13 days*

Treatment.	Time.			Average.	Evaporation loss.
	Morning.	Noon.	Evening.		
					Gm.
Sunshine	30. 2	41. 3	34. 2	35. 2	554. 8
Half shade (cheesecloth)	25. 6	32. 2	28. 7	28. 8	513. 4
Shade (wood)	19. 7	23. 2	24. 6	22. 5	407. 8

Table V shows the total loss in grams for each treatment. Figure 7 shows by graph the average temperature and the total loss with sunshine for part and for complete shade. It is noticeable that the evaporation losses decrease as shade increases.

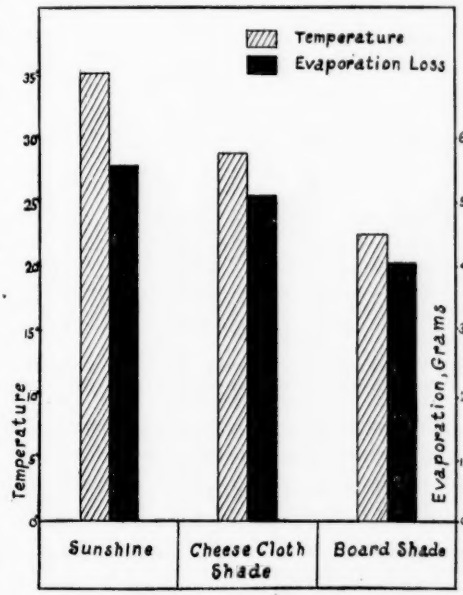

FIG. 7.—Loss of water from soil and temperatures in the sun and under cheesecloth and board shade.

TEMPERATURE

Temperature, relative humidity, and initial quantity of moisture are usually considered to be the most important factors in determining the intensity of evaporation. Perhaps temperature is most active. Fortier (5) shows that a reduction from 88° to 53° F. causes a corresponding reduction in evaporation loss of 85 per cent. These figures suggest the close relationship of evaporation to temperature. This important effect of temperature was made clear in a number of experiments where other factors were being studied.

To get some specific effects of temperature on the rate of evaporation of moisture from the soil, a number of large water baths were so arranged

that they could be kept uniform in temperature to within about one degree. Twenty-five gm. of soil were moistened and then put in flat-bottomed aluminum cans 7 cm. in diameter and 3 cm. deep, the cans being about one-fourth full. In order to bring the temperature of the soil quickly to the temperature of the water, these cans were allowed to float on water in the water baths. The baths were maintained at 20, 30, 40, 50, 60, 70, 80, and 90° C. It was almost impossible to maintain a uniform temperature when the bath was hotter than 90°; and when it was colder than 20° the evaporation was too slow to give noticeable results.

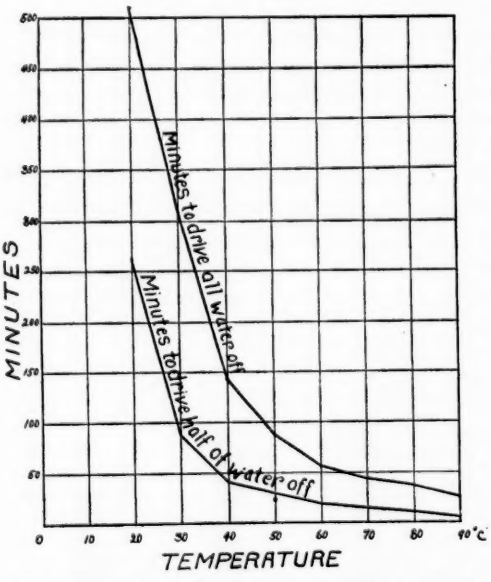

FIG. 8.—Time required at different temperatures to drive off half and all the water from Greenville loam containing 12 per cent moisture.

Two soils were investigated. The first was Greenville loam with an initial moisture content of 12 per cent of the dry weight of the soil and the second was a coarse sand with 20 per cent of initial moisture on the dry basis.

Hundreds of weighings were made to determine the rate of loss with each temperature. These weighings gave the results contained in figures 8 and 9.

The loam containing 12 per cent of moisture required 265 minutes at 20° C. to lose half of its moisture and 510 minutes to become practically dry. At 30°, 89 and 312 minutes were required to make it half and completely dry, respectively; at 40°, 46 and 143; at 50°, 23 and 88; at 60°, 17 and 56; at 70°, 12½ and 45; at 80°, 9½ and 38; and at 90°, 7 and 27.

In sand containing 20 per cent of moisture, the number of minutes required to become half and completely dry respectively at the various temperatures was as follows: At 20°, 315 and 819; at 30°, 90 and 240; at 40°, 45 and 100; at 50°, 30 and 72; at 60°, 13 and 35; at 70°, 9 and 24; at 80°, 6 and 18; and at 90°, 4½ and 13 minutes.

In the loam containing 12 per cent of water as an average, it required nearly three times as long to drive off the last 6 per cent of water as it did for the first 6. In the sand containing 20 per cent, it required more than

twice as long to evaporate the last 10 per cent as it did the first. In each case the last water that was driven off was the hygroscopic moisture. This probably accounts for the greater time required.

SIZE OF SOIL PARTICLES

Since evaporation takes place almost entirely at the surface, the rate of capillary movement directly affects this form of water loss. Because the size of soil particles and the porosity of the soil influence capillary movement, they indirectly affect evaporation. Principi (14) says that materials having the greatest pore space permit greatest evaporation. Wollny (21) reports no capillarity with particles more than 2 mm. in diameter, and also an increase as the particles get finer, though in clay the movement is slow. Losses from below the surface take place, according to Buckingham (2) by diffusion and vary with the square of the porosity of the soil.

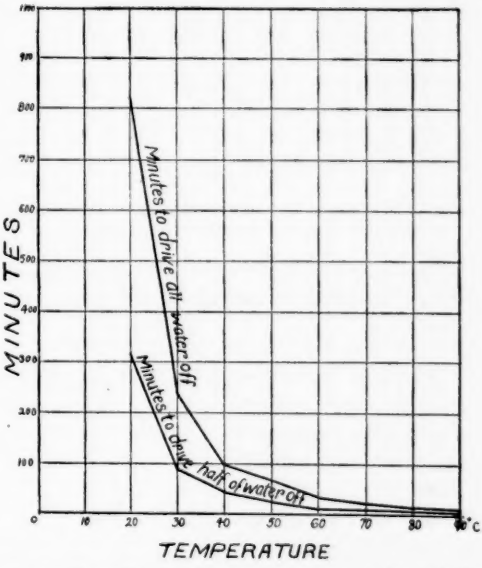

FIG. 9.—Time required at different temperatures to drive off half and all the water from sand containing 20 per cent moisture.

On account of the great difficulty in interpreting the results connected with this phase of the evaporation problem when ordinary soils are used, most of our work has been done with sands having grains of different diameters. The early experiments were conducted with river sands and gravels; but because of greater ease in obtaining uniform size of particles and because of lesser influence due to the composition of the materials, most of the later work was done with graded quartz sand.

In all trials except those in saturated atmosphere beneath the soil, these tests were made in the copper evaporimeters with free water maintained from about 1 to 3 cm. below the surface of the soil, the distance varying in different experiments. At weighings, which occurred about a week apart, the vessels were made up to their original weight.

The results of these tests are presented in figures 10, 11, and 12.

An examination of figure 10 shows a gradual increase in evaporation as the size of particles decrease. There are a number of irregularities probably caused by the difficulty in getting a uniform surface on all the evaporimeters. It will be noted that in some cases the evaporation was greater from the wet sand than from water.

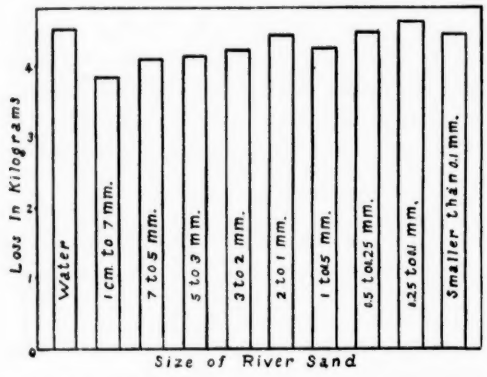

FIG. 10.—Evaporation of water in 66 days from sand of different sizes with a water table maintained 1 cm. below the surface.

In figure 11 results for three grades of pure quartz sand, for Greenville loam, and for water are shown. Here, as in figure 10, the finer grades lose more than the coarser.

Figure 12 includes five sizes of quartz sand, three sizes of river sand, and water. The differences are not marked, but are sufficient to bear out previous results in showing the greater evaporation from the surface of the smaller particles.

MULCHES

Wherever water storage in field soils is important, mulches are used to decrease the evaporation loss. Ridgaway (15) and Fortier (5) both indicate the great saving due to mulches made by stirring the topsoil or by adding covers of dry soil.

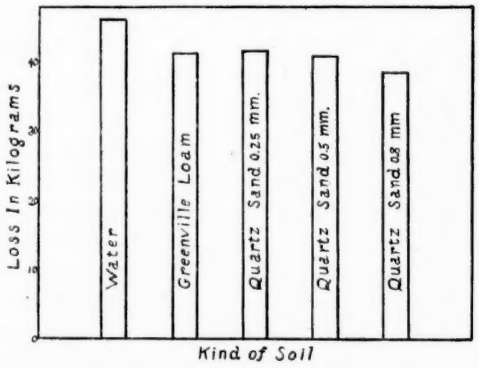

FIG. 11.—Evaporation of water in 36 days from loam and sand of different sizes with a water table maintained 3 cm. below the surface.

A number of laboratory experiments to study the effectiveness of different mulches when the effect of capillarity has been eliminated were conducted. In these experiments the different mulches were suspended above the water. The mulch was placed on wire gauze covered with cheesecloth or on perforated sheet metal to keep it about 1 cm. from the surface of the water in the lower part of the vessels. No water could evaporate except through the mulches.

A study of two sand mulches ½ inch and 1 inch deep, respectively, when placed where the sun would shine on them for half the day for 32 days shows a loss of 57 gm. for a mulch 1 inch deep, 60 gm. for a mulch ½ inch deep, and 155 gm. for the cheesecloth with no dry soil over it. Thus the shallower mulch lost but little more than 5 per cent more than the deeper. The check in which the water evaporated through the cloth and gauze lost nearly three times as much water as that from the mulches. This bears out Fortier's findings in regard to the effectiveness of mulches, but not in regard to the relative value of deep and shallow mulches.

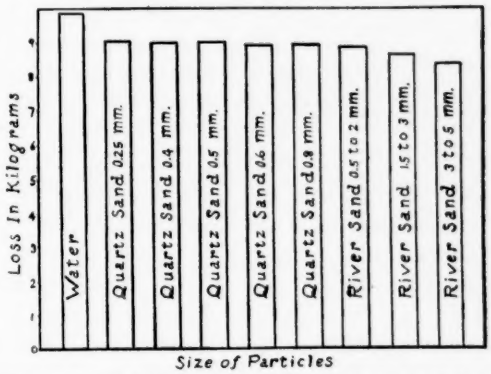
Loss In Kilograms
Water
Quartz Sand 0.25 mm.
Quartz Sand 0.4 mm.
Quartz Sand 0.5 mm.
Quartz Sand 0.6 mm.
Quartz Sand 0.9 mm.
River Sand 0.5 to 2 mm.
River Sand 1.5 to 3 mm.
River Sand 3 to 5 mm.
Size of Particles

FIG. 12.—Evaporation of water in 115 days from quartz and river sand of different sizes with a water table maintained 3 cm. below the surface.

Figure 13 gives the results of the evaporation from 1-cm. mulches of river sands varying in size from 0.1 mm. to 7 mm. for 40 days. The loss is somewhat greater through the smaller sands. When, however, the sizes are larger than 1 mm., the variations in loss are irregular and inconclusive. The mulches prevented over half the evaporation that occurred from free water.

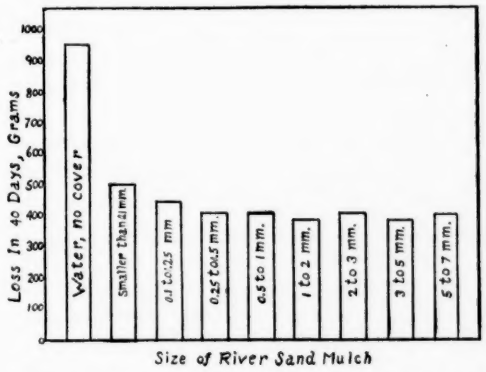
Loss In 40 Days, Grams
Water, no cover
Smaller than 0.1 mm.
0.1 to 0.25 mm.
0.25 to 0.5 mm.
0.5 to 1 mm.
1 to 2 mm.
2 to 3 mm.
3 to 5 mm.
5 to 7 mm.
Size of River Sand Mulch

FIG. 13.—Loss of water from glasses having dry mulches of sand of various sizes suspended above free water.

With perforated aluminum lids 6 cm. in diameter and with a mulch nearly 2 cm. thick, a more exhaustive experiment was conducted. It was similar to the above, except that quartz sands were used for the smaller sizes and that tests with muck, clay, loam, and straw were also run. This experiment continued for a period equivalent to 180 days, the weighings being made at about 10-day intervals. Results of this experiment are shown in figure 14. Of the mulches the greatest loss was through the muck, followed by loam, clay, and straw in order, with the sand mulches

having the least evaporation. The sands show somewhat the same results as were found in the experiments mentioned above, except that there is a tendency for the losses to increase with increasing size of soil particles when the particles are more than 2 mm. in diameter.

COMPACTING THE SOIL

A set of six galvanized-iron cans 13 inches deep and 11 inches in diameter with an opening at the bottom through which water could be added from below to maintain the soil at a constant moisture content were filled with soil. Two sections of the soil at various depths were compacted in order to determine the effect of compacting on evaporation. The cans contained 12 inches of Greenville loam made up to about 15 per cent moisture. In can 1 the surface 2 inches were compacted; in can 2 the second 2 inches; and so on, until in can 6 the bottom 2 inches were compacted. The packed layers contained 20 per cent more soil in a 2-inch layer than a similar volume of the loose soil. These cans were weighed weekly for seven weeks and the loss made up through the side tubes at the bottom, which were kept closely stoppered except while water was being added.

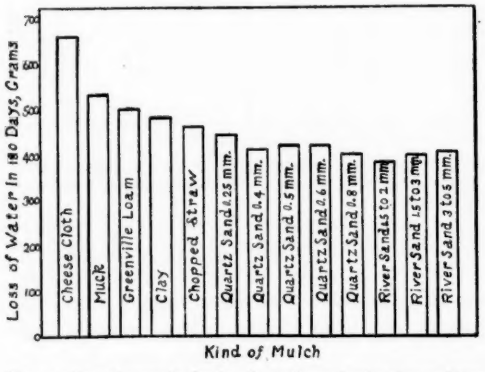

FIG. 14.—Loss of water in 180 days from glasses having dry mulches of various kinds suspended above free water.

Table VI shows that cans 1 and 2, compacted in the first and second 2-inch layers, respectively, lost much more heavily than the cans in which the packed layers were farther from the surface.

TABLE VI.—*Loss of moisture from cans of soil containing a 2-inch section compacted at various depths*

Can No.	2-inch section compacted.	Total loss.
		Gm.
1	Top	1,205
2	Second	1,045
3	Third	885
4	Fourth	870
5	Fifth	880
6	Bottom	805

Compacting the surface caused a marked increase in the loss; packing the second 2-inch section also increased the loss, but only about half as much. Compacting below 4 inches affected evaporation little if any.

METHOD OF APPLYING WATER

An important thing to know where irrigation is practiced is the effect on evaporation of applying water in different ways. Fortier (5) and Widtsoe (19) indicate that a great saving results from applying water in deep furrows or by subirrigation in which the water is added some distance below the surface.

In the summer of 1912 a study with soils 12 inches deep was conducted. Cylindrical vessels 11 inches in diameter and 13 inches deep were filled to within an inch of the top with Greenville loam. An equivalent of 10 kgm. of dry soil was used and made up with moisture ranging from 5.4 to 35.4 per cent in 5 per cent intervals. Weighings were made on three days weekly—usually Monday, Wednesday, and Friday. The losses were made up by adding water through spouts which entered the bottom of the cans and which were kept closed except while water was being added. Thus, the water had to move through 12 inches of soil, rather compact and unstirred, and evaporated from a small surface. Parallel to this test and used as a companion were the large galvanized-iron pans already described under the initial-quantity study. Here the soil was only about 1½ inches deep. To these shallow tanks the water was applied at the surface. The two trials were parallel throughout. The same percentages of moisture were used, weighings were made at the same time, they were run the same period, and the same kind of soil was used. A comparison of the two sets of results may be interesting, as they show the effect of different methods of applying water.

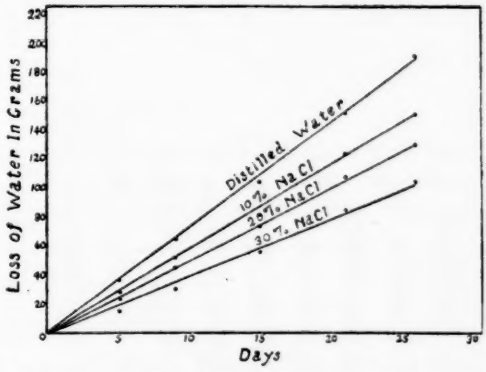

FIG. 15.—Evaporation from distilled water and from sodium-chlorid solutions of different concentrations.

Table VII gives the comparative data. In this table it may be noted that the losses at low percentages were somewhat more rapid from the shallow tanks, but that the deeper cans tended to lose more at the higher percentages. These had no free water exposed on top, while the wetter soils in shallow pans did. As already pointed out, the wet soils often

lost more than the free-water surfaces. The deeper soils were also more uniformly wet. Capillarity doubtless played a part in this experiment.

TABLE VII.—*Comparison of evaporation from large areas and shallow soil with small areas and deep soil, 10 kgm. of Greenville loam being used in each case*

Soil moisture.	Shallow tanks.			Deep cans.		
	Surface area.	Total evaporation.	Evaporation for each square foot of surface.	Surface area.	Total evaporation.	Evaporation for each square foot of surface.
Per cent.	*Sq. feet.*	*Gm.*	*Gm.*	*Sq. feet.*	*Gm.*	*Gm.*
5.4	5.42	2,935	542	0.66	270	409
10.4	5.42	6,100	1,125	.66	440	666
15.4	5.42	7,770	1,434	.66	700	1,066
20.4	5.42	7,405	1,366	.66	920	1,395
25.4	5.42	8,299	1,531	.66	1,010	1,530
30.4	5.42	8,415	1,553	.66	995	1,500
35.4	5.42	8,985	1,658	.66	1,270	1,939

SOLUBLE SALTS

The effect of dissolved salts in reducing the vapor tension, and consequently the evaporation of solutions, is well known. The action of these salts in the soil on evaporation, however, is not so clear, since secondary factors may be introduced. In the ordinary agricultural soil the concentration of soluble salts is not sufficient to have any marked effect on evaporation, but in the alkali soils of arid regions salts may be present in sufficiently high concentrations to affect the loss of moisture materially.

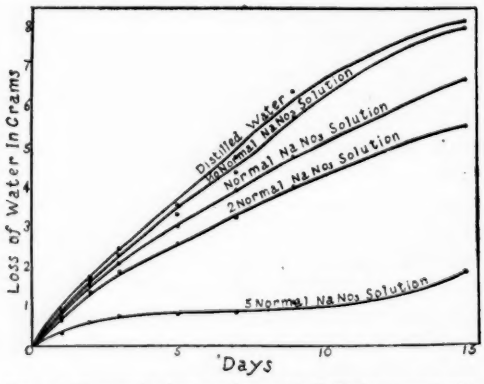

FIG. 16.—Evaporation from sand wet with distilled water and with sodium-nitrate solutions of differ ent concentrations.

With a view to determining some of the effects of salts on evaporation, a number of experiments were conducted. In the first, solutions of sodium chlorid of various concentrations without soil were investigated. The solutions were placed in glass tumblers, two tumblers being used for each treatment, and set in the open laboratory where evaporation could go on freely. The tumblers were weighted every few days and the loss made up with distilled water.

The results of this test are shown in figure 15, which brings out clearly the fact that as the concentration of the solution increases the evaporation decreases.

The second test was conducted in porcelain crucibles, each containing 10 gm. of quartz sand which had been wet with 4 c. c. of solutions of sodium nitrate ranging in concentration from a check solution containing no salt up to 5 times a normal solution. There were two crucibles for each concentration. The crucibles were placed under a bell jar in order to avoid air currents and to keep the humidity as uniform as possible over all the crucibles.

Weighings were made each day at first, and every two or three days later. The experiment was begun January 12 and continued till January 27, making a period of 15 days.

The results are given in figure 16, which shows a decrease of evaporation from the sand the same as when the solution of sodium nitrate is added. A third test was conducted in galvanized-iron cans, 11 inches in diameter and 13 inches deep, partly filled with Greenville loam to which sodium chlorid was added in different quantities, ranging from the control containing nothing to 7 per cent of the dry soil. The quantity of moisture that evaporated was added every three or four days through a tube near the bottom of the cans. In this way the surface of the soil was never disturbed, but there was a gradual accumulation of salts at the surface. The experiment ran from August 19 to September 25.

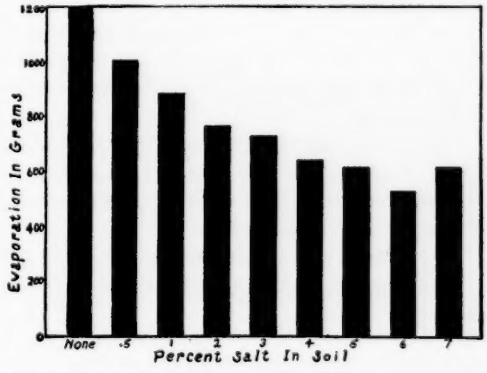

FIG. 17.—Evaporation of water from Greenville loam containing different quantities of sodium chlorid.

The results of the experiment are given in figure 17. There is a gradual decrease in the evaporation as the salt content of the soil is increased. The can with 7 per cent of salt lost slightly more than that with 6 per cent. This irregularity was doubtless due to the fact that considerable salt was crystallized at the surface of the soil in this can, consequently the real concentration of the solution was decreased; and it is the salt actually in solution that affects vapor tension.

From these experiments it seems clear that soluble salts in the soil decidedly decrease the evaporation of moisture if the concentrations are high, but the reduction is only slight for the solutions found in ordinary soils.

SUMMARY

(1) The conservation of soil moisture is one of the most important problems of agriculture, particularly in arid regions.

(2) One of the important factors involved in water conservation is evaporation.

(3) In this paper a study has been made of a number of the factors having to do with evaporation.

(4) Evaporation of moisture increases with the initial quantity in the soil. The increase is not so great with the higher percentages as with the lower, and there seems to be a number of critical points where the rate of loss changes rapidly.

(5) The rate of evaporation from a moist soil is very rapidly decreased as the humidity of the air is increased.

(6) Air currents greatly increase evaporation; but after about a certain wind velocity is reached, the rate of evaporation is only slightly increased by increasing the wind velocity.

(7) For the sizes investigated, evaporation was higher from the finer soil particles than from the coarser when both are completely saturated.

(8) Reducing the intensity of sunshine greatly reduces the rate of evaporation.

(9) Slight changes in temperature have a marked effect on evaporation.

(10) A thin mulch, if kept dry, is effective in reducing evaporation. Dry mulches, composed of fine particles, seem to be less effective than if composed of coarser particles.

(11) Compacting the surface of the soil increases evaporation.

(12) Dissolved salts in high concentrations reduce the evaporation of moisture from soils.

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